SEISMIC INVESTIGATIONS IN THE COLOMBIA, VENEZUELA AND GRENADA BASINS, AND ON THE BARBADOS RIDGE FOR FUTURE IPOD DRILLING

B. BIJU-DUVAL[1], A. MASCLE[1], L. MONTADERT[1]
& J. WANNESON[1]

ABSTRACT

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The geological setting of five sites for future IPOD drilling in the Caribbean is described. These sites were surveyed in 1976 by IFN-CNEXO with 2800 km of multichannel seismic records.

The first two sites straddle the lesser Antilles island arc where the oceanic Atlantic plate is subducted westwards under the Caribbean plate. The main objectives of these sites are to investigate the frontal overthrust of the Barbados Ridge (accretionary prism) on the Barracuda abyssal plain, and the age and nature of sediments and crust of the back arc basin, e.g. the Grenada Basin.

The three other sites are located in the Venezuela and Colombia Basins in order to understand their composite structure better and to compare their geological history with the geological evolution of their surrounding margins.

INTRODUCTION

The Caribbean Sea, with its small oceanic basins between the Atlantic and Pacific oceans, is associated with the development of more or less typical active margins. It is an area where different basic geological problems could be solved. An understanding of them would make it possible (1) to define the nature of Layer 2 in such a small ocean basin better, (2) to study the different features associated with an island arc, and (3) to shed some light on the history of water-mass communications between the Atlantic and Pacific via the Caribbean.

(1) The basins in the Caribbean Sea still remain enigmatic for reconstructions of the opening of the equatorial Tethysian Atlantic. Are their basements older segments of Pacific or of Tethysian Atlantic crust? Did they originate by inter-arc spreading? Earlier DSDP drillings penetrated the sediments and ended in dolerite/basalt immediately overlain by deposits of late Cretaceous age. But we do not know the true thickness and age of inception of this widespread topmost expanse of Layer

(2) Moreover, as shown in Fig. 1, the Caribbean is characterized by different active margins comparable to other typical active margins in the world. New drilling sites could give a transect through the lesser Antilles Island Arc from the accretionary prism on the Atlantic side to the back arc basins (Venezuelan and Colombian Basins).

(3) Acquisition of a biostratigraphic section as complete as possible from the Colombian Basin should be very useful for determining the history of Late Cretaceous to Recent water-masses on the Caribbean side of the Panama Isthmus with the corresponding history on the Pacific side. Using comparison with previous data from onshore studies and offshore results (Legs 4 and 14), the implications of the palaeoenvironment could be very important.

Following a long list of onshore and offshore geological and geophysical surveys involving worldwide international participation, a drilling proposal in the Caribbean Sea has been put forward by the Mediterranean-Caribbean subpanel of IPOD with the collaboration of numerous geologists and

[1] Institut Français du Pétrole, Division Géologie, B.P. 311, 92506 RUEIL-MALMAISON Cedex, France.

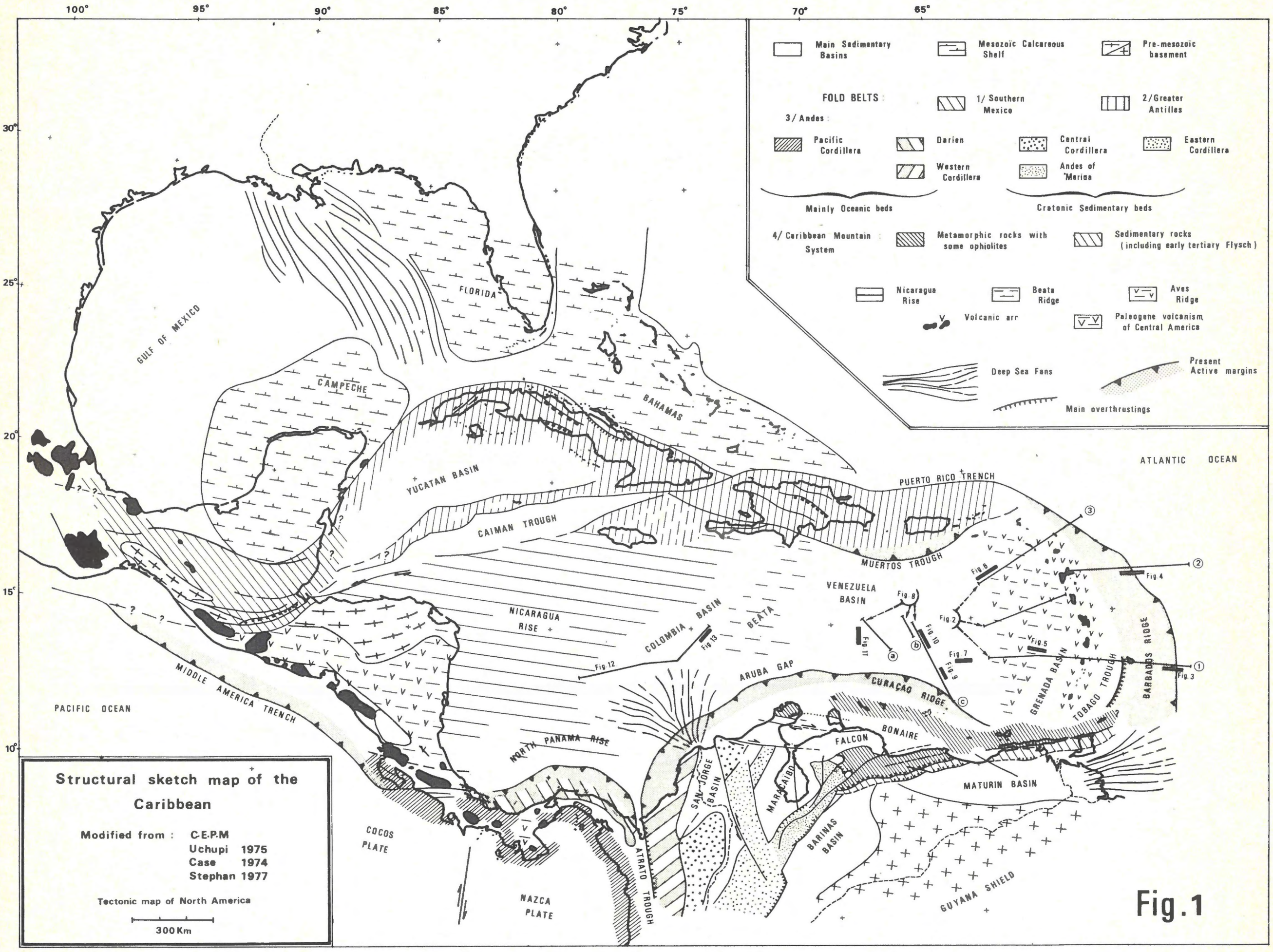

Fig. 1
Structural sketch map of the Caribbean and location of the sections and multichannel seismic lines.

geophysicists. Appointed by the Planning Committee of IPOD, the subpanel finalized the proposal at Galveston, Texas, in January 1977, taking into account numerous data from institutions or Oil Companies (UTMSI, IFP-CNEXO, LDGO, CEPM, SHELL, GULF).

We will now describe the geological setting of the five sites surveyed by IFP-CNEXO (R/V Florence) in April 1976 and shortly described in the Mediterranean-Caribbean subpanel's proposal. For this 2800 km survey, multichannel seismic recording was used with on board processing in real time, total magnetic field recording and several sonobuoy records. A more detailed study of these site surveys and of their geological framework will be published in a forthcoming paper. For the illustration of the geological setting of the sites, we also used some 24 fold CEPM multichannel seismic lines.

LESSER ANTILLES ISLAND ARC

Subduction of the Atlantic plate under the Caribbean plate has resulted in the building up, since the Eocene and perhaps since the late Cretaceous, of an Island Arc whose structural elements will be described from east to west (Fig. 2).

(1) In front of the Arc the age of the subducted Atlantic *oceanic crust* is unknown. But according to the magnetic anomaly identification (PETER & WESTBROOK, 1976) it is at least of Late Cretaceous age. These authors have also shown that the oceanic crust is cut off by E-W trending faults that are seismically the active extension of Atlantic transform faults. Some of them have a topographical expression on the sea bottom; for instance the 15°30' fault zone could be traced westward in the Barracuda Rise.

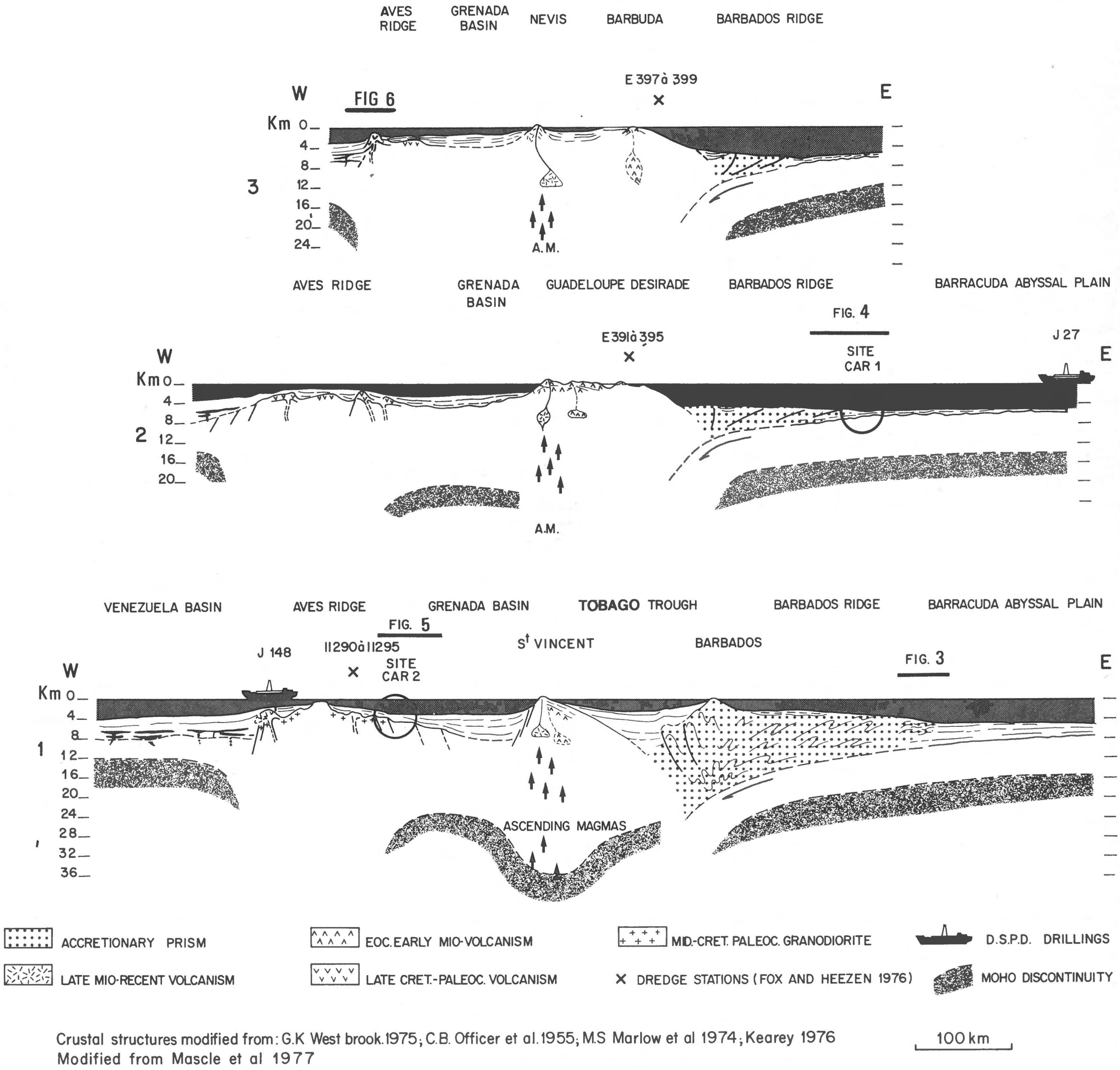

Fig. 2
Cross-sections through the Lesser Antilles Island Arc. Location on Fig. 1.

To the south and close to the South American continent, the abyssal plain is covered by an unusually thick sedimentary layer (more than 4000 meters at the latitude of section 1 in Fig. 2).

(2) The Lesser Antilles Arc is never marked by a topographical *trench* except to the north between 17°N and 19°30'N where a trench corresponds to the southeastern end of the Puerto Rico Trench. To the south, this trench is buried under the increasing thickness of sediments that have been accumulated and deformed to build an accretionary prism.

(3) The *accretionary prism* is well developed in the southern part of the arc, constituting the Barbados Ridge. It is 300 km wide and up to 20 km thick at the latitude of Barbados (Fig. 2, section 1; WESTBROOK, 1975). It emerges locally above sea level on the island of Barbados. Here the outcropping sediments are mainly of Tertiary age. They consist

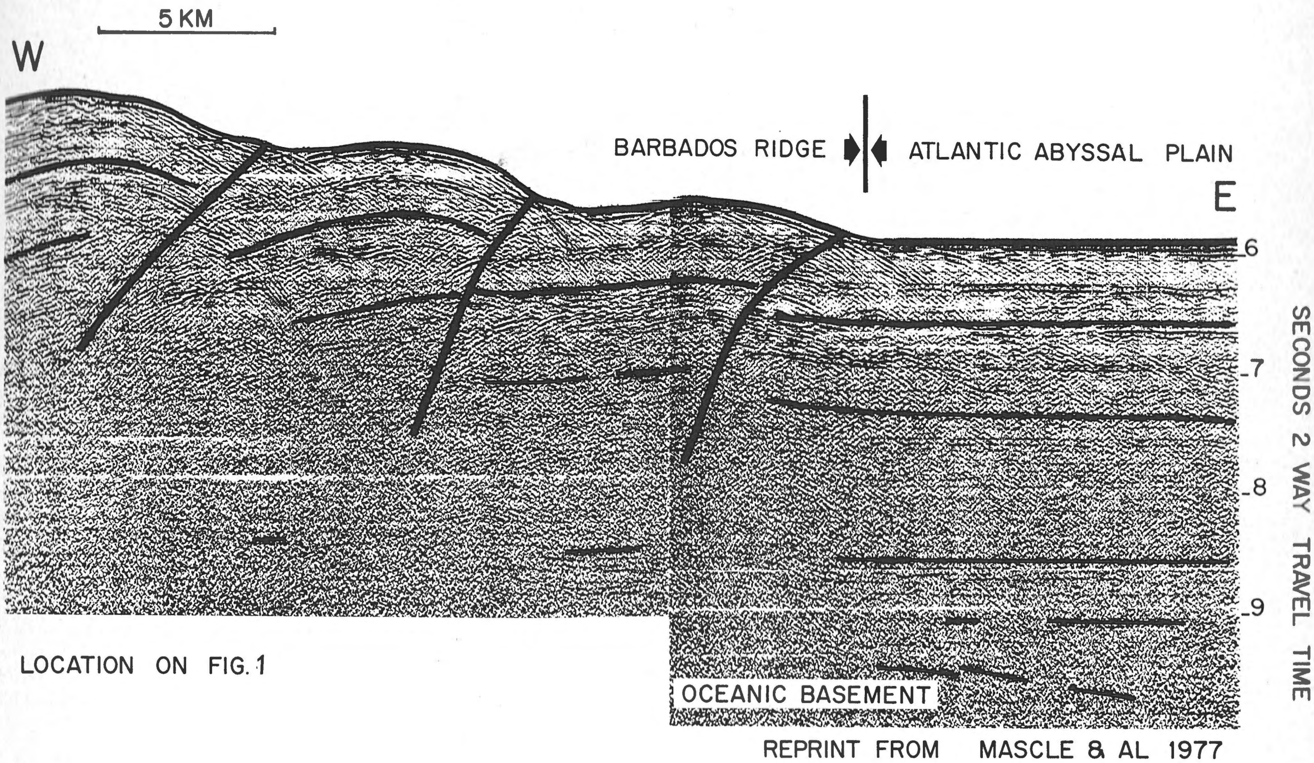

Fig. 3
CEPM Multichannel seismic line 108 A. Location on Fig. 1 and 2.

of early Tertiary turbidites originating in both shallow and deep water, of pelagic early-mid Tertiary sediments and of Neogene uplifted coral rocks (for more details, see SAUNDERS, 1968, 1977). The turbiditic and pelagic units are both tectonically deformed, but the structural style of deformation is not well known due to the scarcity of outcrops.

This accretionary prism thins out northwards (Fig. 2, sections 2 and 3). It is quite small north of the Tiburon Rise where it is also known as the Lesser Antilles Rise (MARLOW ET AL., 1974).

The tectonic style of deformation in front of the Barbados Ridge is quite different in the northern and southern part of the arc. To the south, where at least 4000 m of sediments are involved, compressions have formed broad anticlines with thrusting to the east (Fig. 3). To the north, for instance between the Tiburon and Barracuda Rises, the tectonic style of deformation is far less obvious (Fig. 4). To the east, a unit with no coherent reflectors overthrusts the oceanic Atlantic crust and the lower part of its sedimentary cover. If the tectonics of the whole Barbados Ridge are linked to the westward underthrusting of the Atlantic crust, the tectonic style of the frontal deformations (horizontal thrust faults, gravity slides, etc. . . .) is still unclear.

A Deep Sea Drilling site has been proposed and surveyed in this area in order to solve at least three major points (Fig. 4):

- Tectonic nature of the front of the accretionary prism.
- Age and lithology of the autochthonous sediments of the Atlantic abyssal plain, in place under the allochthonous unit.
- Age of the Atlantic oceanic crust. Comparison with the 'ophiolitic' assemblage outcropping on Desirade island.

(4) On the back part of the accretionary prism, the Tobago Basin is a well developed and thick outer arc basin. Surface sediments are silty clays with, locally, some large amounts of sand (KELLY ET AL., 1972). These sediments are deformed on the eastern rim of the basin, in such a way that the undisturbed sediments in Tobago Basin are accreted eastwards to the Barbados Ridge (MASCLE ET AL., 1977; Fig. 2, section 1). A deep-sea drilling site would be very interesting to date the tectonic events, facies and the origin of sediments. Safety considerations have prevented such proposals from being carried out.

(5) The volcanic arc is relatively narrow from Grenada to Dominica, and much wider to the north (Fig. 1). The Tertiary evolution of the arc has already been well described (see for instance TOMBLIN, 1975; WESTERCAMP, 1977). The

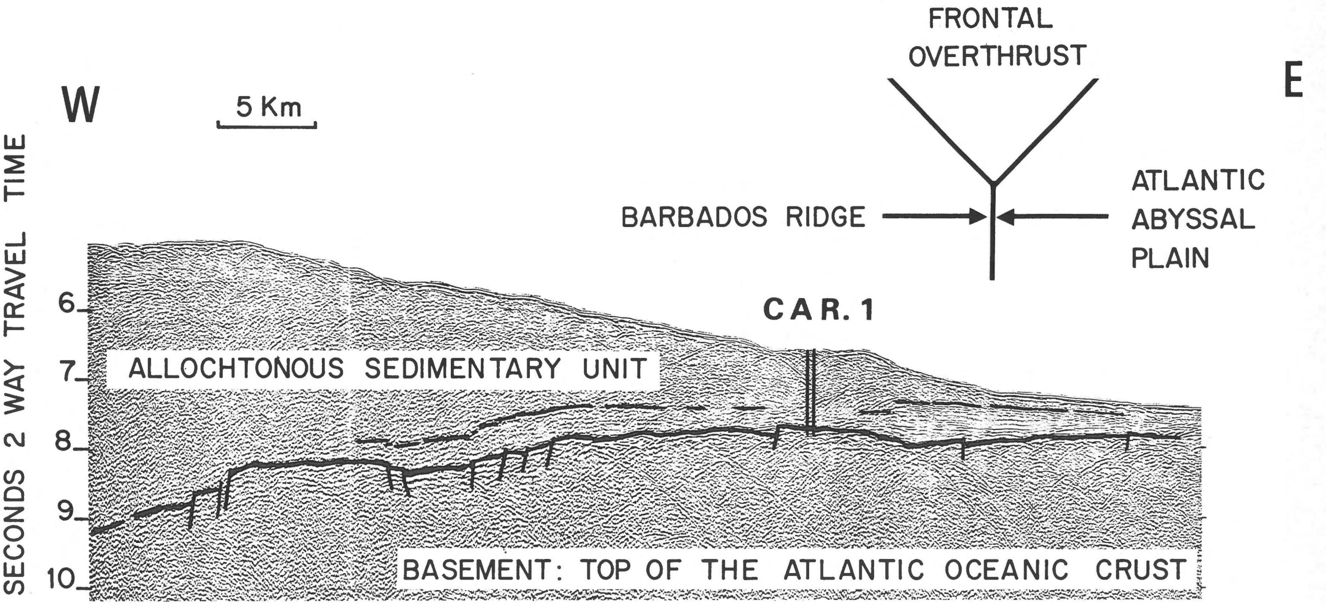

Fig. 4
CEPM Multichannel seismic line A4. Location on Fig. 1 and 2.

northern part of the Neogene arc, from Basse Terre (Guadeloupe) to Saba, is shifted westward with respect to the northern part of the Palaeogene volcanic arc, from Grande Terre (Guadeloupe) to Sombrero, where they are superimposed to the south. Then to the north, the extinct Palaeogene volcanic arc acts like a frontal arc. It is separated from the Neogene volcanic arc by a mid-sedimentary basin according to the terminology of RAVENNE ET AL. (1977) (Fig. 2, section 3). This basin is filled with 1000 or 2000 meters of sediments, probably calcareous and volcano-clastic.

(6) Behind the volcanic arc, the Grenada Basin is a large back-arc basin. It is especially well developed to the south where it looks like an asymmetrical basin. Maximum sediment thickness is found close to the volcanic arc (Fig. 2, section 1). To the north water depth decreases, and the volcanic arc, Grenada Basin and Aves Ridge merge into a single plateau (including Saba Bank; Fig. 2, section 3).

Several hypotheses could be made about the origin of this back-arc basin:

- Is it an inter-arc basin created by extension behind the Lesser Antilles volcanic arc in the Tertiary?
- Is it a basin created after a jump in volcanic activity from Aves Ridge to the Lesser Antilles in the early Tertiary i.e. an eastward jump of the subduction zone?
- Is it a collapsed basin superimposed on a very broad volcanic plateau, including Aves Ridge and the Lesser Antilles?

The age and nature of the basement would be different in each case, i.e. oceanic crust, deformed sediments, old intrusives or metamorphic rocks.

This could be resolved by deep sea drilling in an area at the latitude of St Vincent, which has already been surveyed in detail. Furthermore, data on the lithology, facies changes and age of the sediments would provide a complete record of the Tertiary history of the basin. Seismic reflection data obtained by site surveying on the western rim of the basin indicate that four sequences are present (Fig. 5):

- An acoustic basement with a rough surface which probably can be correlated with the 5.3 km/second of OFFICER ET AL. (1959) (Unit A).
- An overlying, generally east-dipping sequence which can be seismically followed from the Aves Ridge eastward beneath the Grenada Basin (Unit B).
- Horizontal, bedded sequences up to 3000-4000 meters thick that are restricted to the Grenada Basin itself. Locally, the lower part (Unit C) appears to abut against the dipping sequence of the Aves Ridge flank, while the upper one (Unit D) merges laterally into the upper part of this dipping sequence. This transition corresponds to a change in seismic character which suggests a possible facies change.

(7) Aves Ridge is an elongated structure running from the northern shelf of Margarita Island to the Neogene Lesser Antilles Island Arc, south of the Anegada Passage (Fig. 1). Its general N-S trend is thus slightly oblique with respect to the arcuate trend of the volcanic arc. Previous seismic investigations have shown the general structure of the Ridge (BUNCE ET AL., 1970; KEAREY, 1976). The main

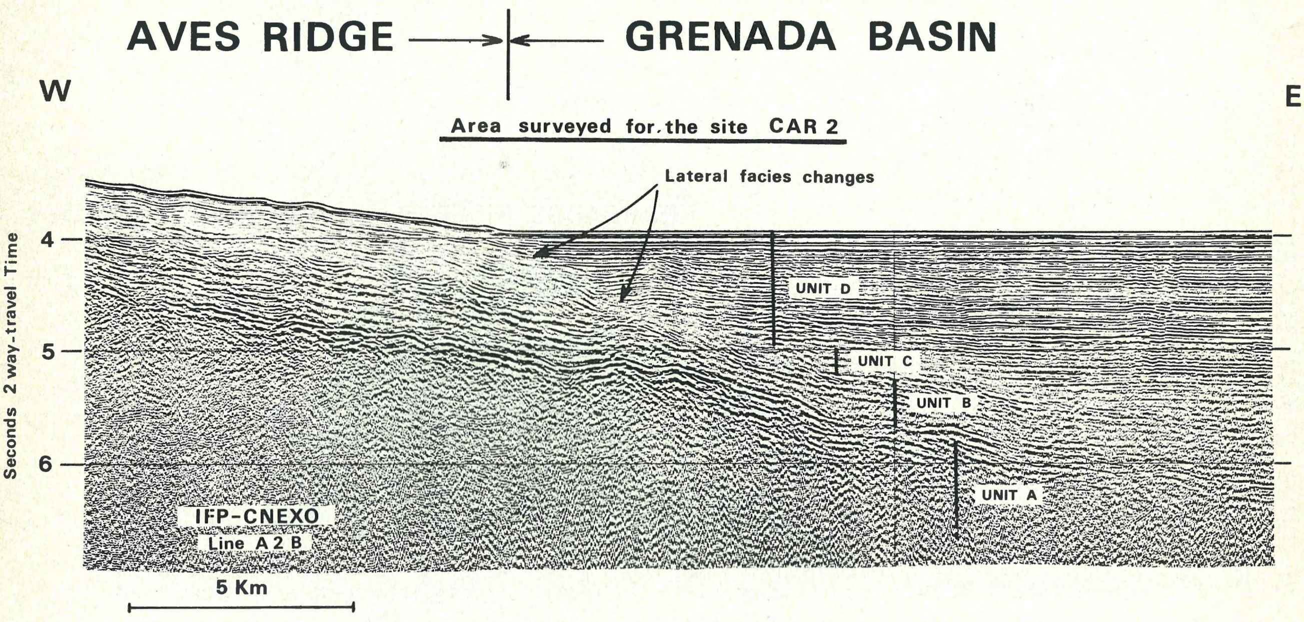

Fig. 5
IFP-CNEXO Multichannel seismic line A2B. Location on Fig. 1 and 2.

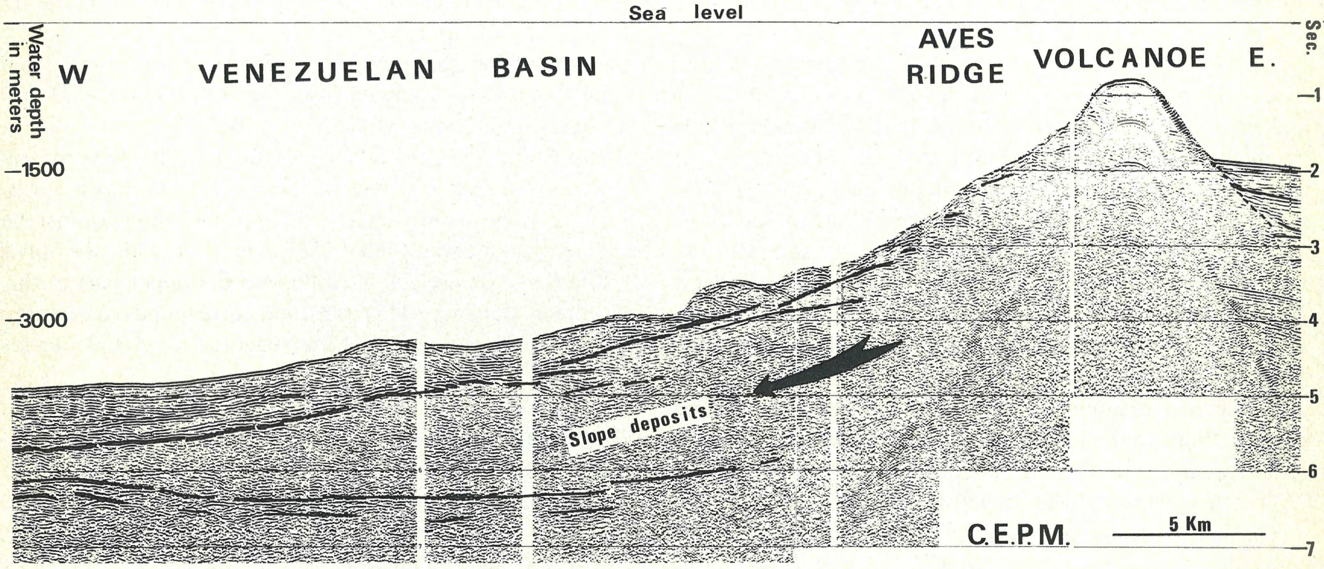

Fig. 6
CEPM Multichannel seismic line 213 A. Location on Fig. 1 and 2.

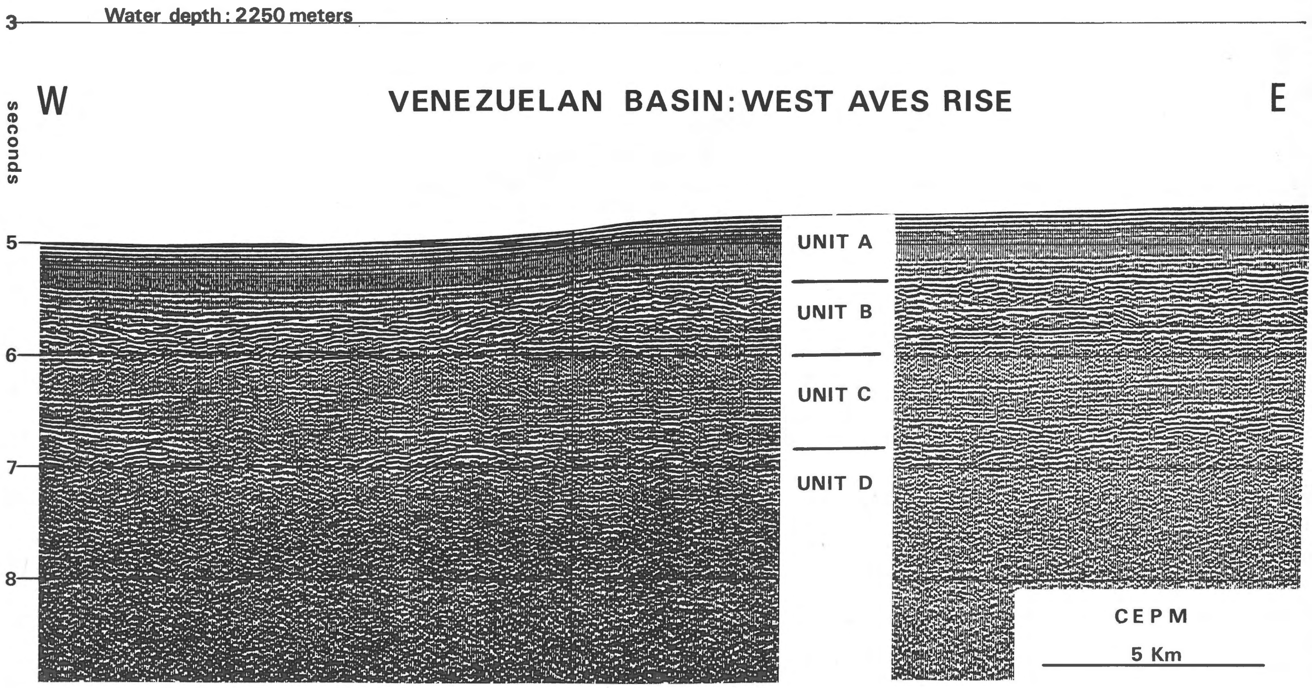

Fig. 7
CEPM Multichannel seismic line 119 A. Location on Fig. 1 and 2.

characteristic of the ridge is the presence of numerous seamounts interpreted as former volcanoes. As a matter of fact, dredging on their flanks brought up volcanic rocks and, locally to the south, granodiorite of upper Cretaceous-Palaeocene age (FOX ET AL., 1971; NAGLE, 1972). Such volcanoes are particularly obvious on some of our lines (Fig. 6) where it is also possible to recognize to the west, i.e. towards the Venezuela basin, a palaeo-slope possibly made of lava and ash flows or of eroded volcano-clastic rocks. DSDP holes 148 and 30, and other dredgings, have encountered sedimentary rocks of mainly Tertiary age. They suggest that, on the top of the ridge, Eocene to lower Miocene neritic conditions were followed by a mid-Miocene-Holocene deep-sea marine sedimentation.

VENEZUELA BASIN

Initial geophysical investigations and drillings were essentially situated in the central and western parts of the Venezuela Basin. Such restricted investigations, made on the basis of single-channel seismic profiles and refraction data, have led to the currently accepted idea that the whole basin is homogeneous. It is supposed to be made of a thick oceanic crust whose top coincides with the unusually flat B'' reflector. DSDP hole 146 indeed encountered a basaltic layer at a depth equivalent to this reflector. Nevertheless multichannel seismic profiles have shown that coherent reflectors exist below B'' (HOPKINS, 1973; WATKINS ET AL., 1977). These infra B'' reflectors could be internal multiples, but their high velocity (ranging from 4.5 to 5.3 km/sec) and sometimes their inverse dipping with respect to B'' argue that they are direct primary reflections. The sedimentary sequence above B'', named the 'Carib Beds', was thought to be widespread in the whole basin. Two major units were distinguished:

- A Turonian-lower Eocene pelagic indurated sequence, with some occurrence of cherts. The top of this sequence was correlated with reflector A'' of Middle Eocene age in hole 146.
- A Middle Eocene-Holocene semiconsolidated to unconsolidated pelagic sequence.

In the DSDP holes transect 146-29-150, important hiatuses were discovered in this sequence, mainly for the Santonian-Palaeocene and early Eocene-early Miocene intervals. These hiatuses are supposed to be due to nondeposition in relation either to palaeocurrents (EDGAR, 1973; HOLCOMBE ET AL., 1977) or to the dissolution of carbonates.

With the surveys now available, using multichannel seismic recording, this general description of the Venezuelan Basin now appears more complicated. For instance, at least 2 areas in the basin show a sedimentary sequence and a basement quite different from the previously described central and western parts of the basin.

(1) West of Aves Ridge, the depth of the sea bottom increases

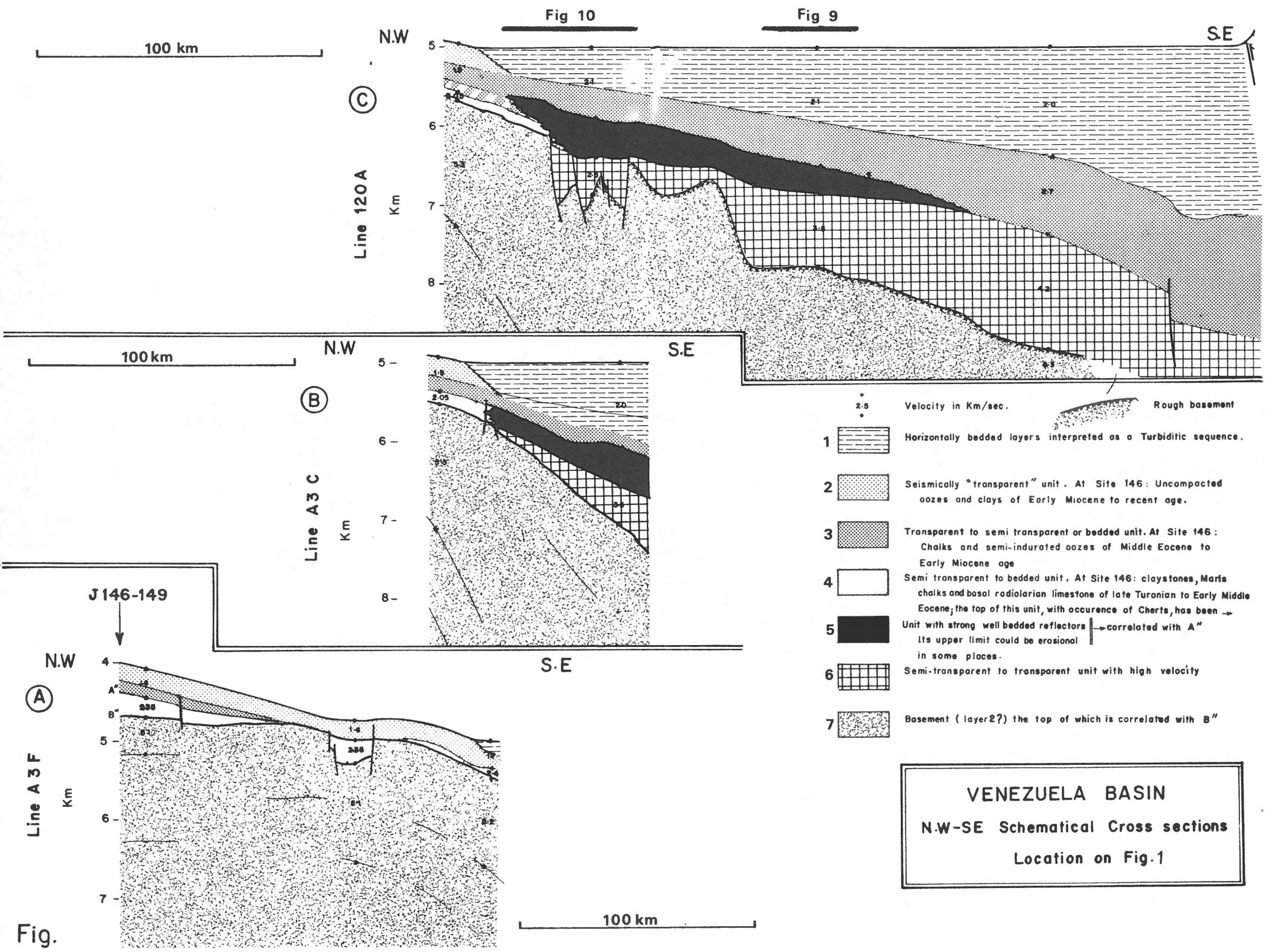

Fig. 8
Sections through the Venezuela basin with a very contracted horizontal scale. Location on Fig. 1.

from 3000 meters to 4800 meters, constituting a nearly 200 km wide rise called West Aves Rise. At the foot of Aves Ridge, sedimentation was partly under the control of volcanic activity (Fig. 6). Farther west, a type section on the rise shows (Fig. 7) a more than 2 seconds thick sedimentary sequence. It is made of 3 main seismic units (a transparent unit A of Neogene age is followed by wellbedded unit B and by transparent unit C). The underlying unit (unit D) is not well defined. It could be either the basement or a fourth and deeper sedimentary unit.

(2) The deeper southeastern part of the Venezuela Basin (below 5000 m of waterdepth) shows a deepening of the basement and a thickening of sediments with respect to the central and western parts of the basin (Fig. 8). In this deeper part of the basin, the sedimentary sequence is made of 4 seismic units (Figs. 8 and 9). They lie on an oceanic-like basement with a rough morphology, equivalent to but quite different drom reflector B''. It has a velocity of 5.5 km/sec (TALWANI ET AL., 1977) to 6.3 km/sec (OFFICER ET AL., 1959). Some intra-basement reflectors are present from place to place, but their nature is unknown.

The most obvious sedimentary change occurs in the Neogene-Quaternary beds. The northwestern pelagic sediments (unit 2 of Fig. 8) gradually merge into a thick turbiditic sequence to the southeast (unit 1). This lateral turbiditic infilling is probably due to the tilting of the basin toward the south. The age of this tilting (Miocene, according to the extended results of DSDP hole 146) could correspond to the initiation of the underthrusting north of the Venezuela margin. However, it is also possible that older turbidites or trench deposits have been included in the accretionary prism, i.e. Curaçao Ridge; they could then represent an earlier stage of subduction.

Below the turbiditic sequence (unit 1), a semitransparent unit (unit 3) is probably equivalent to some northwestern pelagic beds.

Below and laterally equivalent to these older northwestern

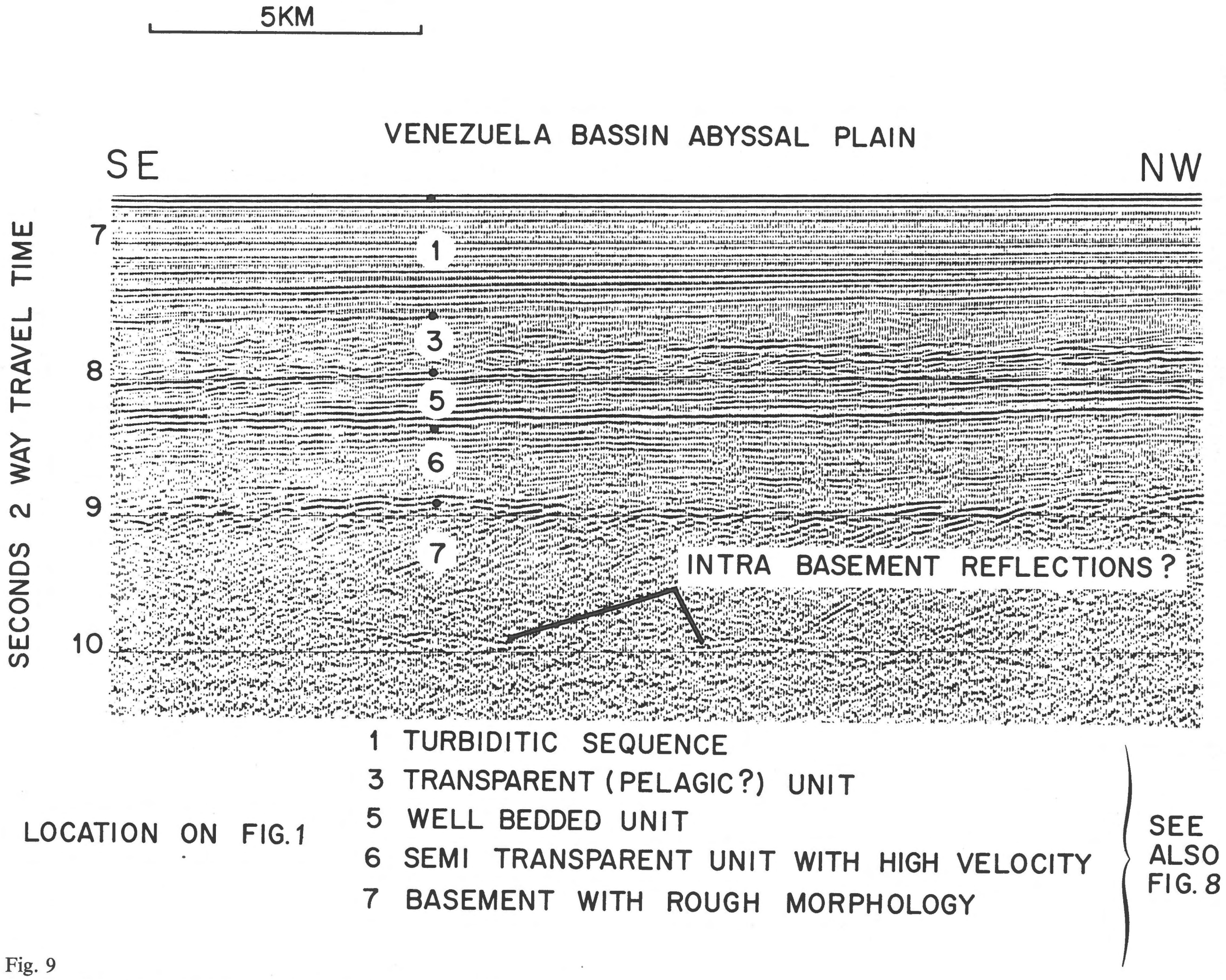

Fig. 9
CEPM Multichannel seismic line 120 A. Location on Fig. 1 and 8.

pelagic beds (unit 4), a unit appears with strong well-bedded reflectors (unit 5). Its upper surface is quite irregular, and could be erosional in some places (Fig. 8, section B). It could correspond to the Middle Eocene palaeo-oceanographic event (BERGGREN & HOLLISTER, to be published). To the southeast, it seems to pass laterally into the lower part of transparent unit 3.

Finally, below it there is a semitransparent unit (unit 6) with high velocity. It seems to be restricted to the deeper part of the basin or is too thin to be seismically identified northwestward.

The transition between the northwestern smooth basement (B'') and the rough oceanic-like basement of the deeper part can be either progressive or marked by a steep fault zone which we call the Central Venezuelan Basin fault zone (C.V.B. fault zone).

Because of these different types of basements and sedimentary infillings, the geological history of the Venezuela Basin cannot be explained as a whole. In order to understand the nature of each part of the basin better and to compare them, we have surveyed 2 sites for a deep-sea drilling proposal:

- Site CAR 3 is situated in the C.V.B. fault zone (Fig. 10). Its goals are (1) to sample the oceanic-like basement and to compare its age and lithology with reflector B''; (2) to date and define the main facies changes and to correlate them with the tectonic events on the Venezuelan borderland.
- Site CAR 4 is situated in the western part of the basin, a few miles west of the previous site 150, in an area where the sedimentary cover is very thin (less than 200 meters thick, Fig. 11). Its main goal is to penetrate into the basement underneath B''. It could have some wide ranging implications with regard to the origin and structure of layer 2 in this region. Very useful comparisons could also be made with the Middle to Upper Cretaceous volcano-sedimentary sequence outcropping in Haiti, which some authors (BUTTERLIN, 1976; MAURASSE, 1977) have already compared with the western Venezuela Basin basement.

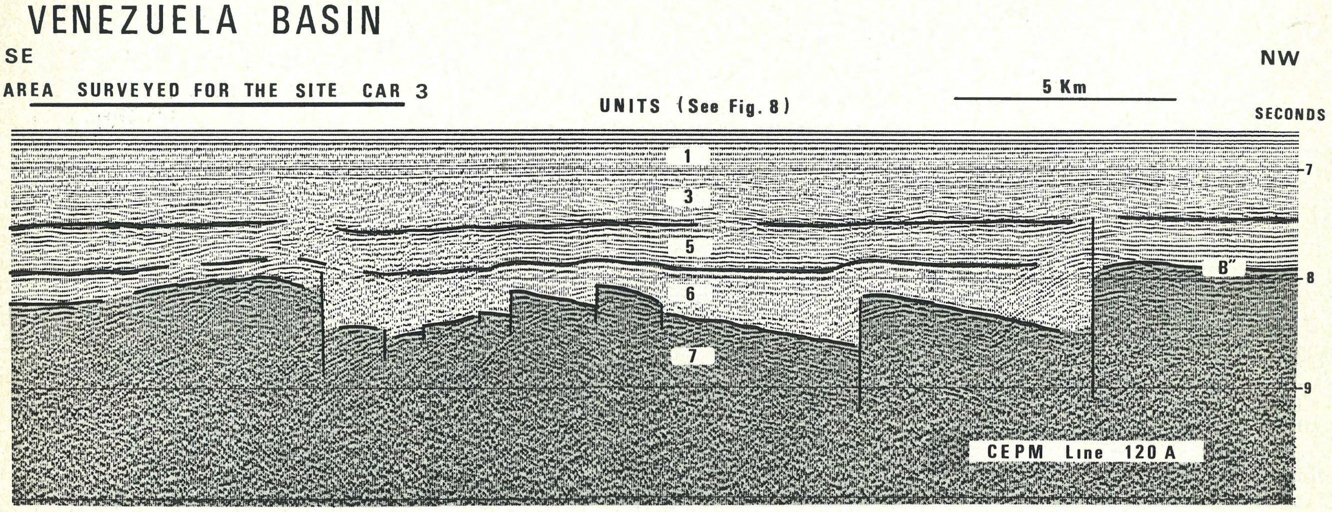

Fig. 10
CEPM Multichannel seismic line 120 A. Location on Fig. 1 and 8.

COLOMBIA BASIN

Data from recently published airgun sonobuoy profiles (HOUTZ & LUDWIG, 1977) and from multichannel reflection profiles (this paper) indicate that the Colombia Basin is a complex arrangement of buried ridges and basins.

To the south, an arcuate ridge, the north Panama Ridge, separates an arcuate trench in front of the north Panama active margin from a broader basin where the Magdalena deep-sea fan is situated. To the north, this ridge seems to be linked to the Nicaragua Rise through the smaller Roncador Rise. The Colombia Basin has 2 elongated extensions; one to the northeast separates the Nicaragua Rise from the Beata Ridge up to Haiti, and another to the east runs up to the Venezuelan Basin and is known as the Aruba Gap. The southeastern rim of the Colombia Basin can be interpreted as an active margin. It is connected to the east with the north Venezuelan active margin. But although the present history of these 2 margins seems to be identical, their past evolution, particularly in the upper Cretaceous and Palaeocene-Eocene times, seems to be quite different (BIJU-DUVAL ET AL., 1977). These differences could be linked to the fact that they face two distinct oceanic domains perhaps of different age and origin. On the other hand, previous DSDP holes 152 and 154 on the flank of the Nicaragua Rise and Beata Ridge suggest a similar origin.

This is why deep-sea holes have been proposed in the deep Colombian basin. We have surveyed a site named CAR 5 in an area between Beata Ridge and Nicaragua Rise, where the basement could be reached. We have added to this survey a 300 km long profile running accross the distal part of the Magdalena Deep Sea fan (Fig. 12). This profile shows the relationship between the deep-sea fan and a depressed part of the basement. Sonobuoy stations reported by Houtz and Ludwig have shown that this depression is on top of a thin crust only about 8 km thick.

The four main objectives of this site would be:
- Age and nature of the basement and comparison with the results of DSDP holes 152 and 154, and with those in the Venezuela Basin.
- Age and lithology of the different sedimentary units (Fig. 13), and importance of the sedimentary influxes coming from the Magdalena River.
- Test of some recent magnetic anomaly models (CHRISTOFERSON, 1973, 1976).
- Acquisition of a complete biostratigraphic section in the Colombia Basin for a comparison of the late Cretaceous to Recent watermasses on the Caribbean side of the Panamanian isthmus with the corresponding history on the Pacific side.

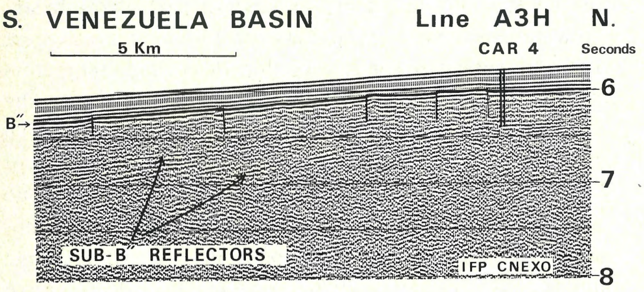

Fig. 11
IFP-CNEXO Multichannel seismic line A3H. Location on Figure 1.

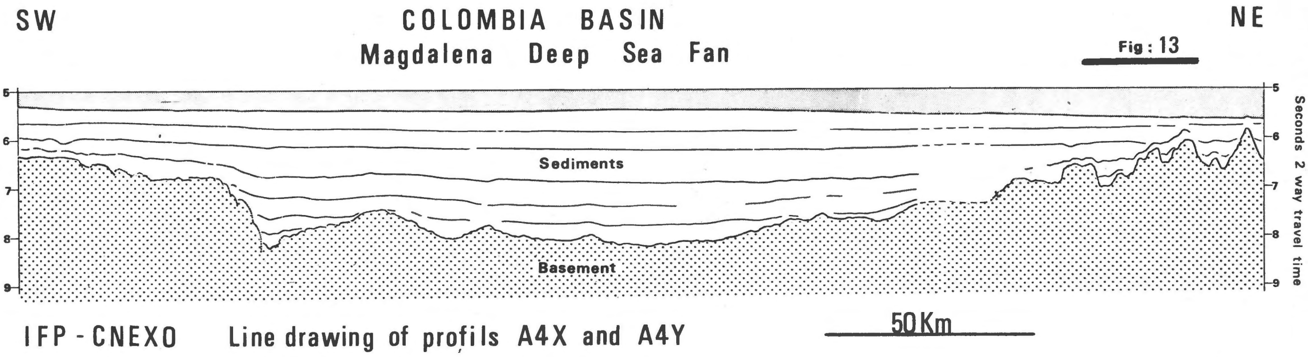

Fig. 12
Line drawing of the IFP-CNEXO, Multichannel seismic line A4X and A4Y.

CONCLUSIONS

The multichannel seismic reflection data presented in this paper clear up some geological problems concerning the Caribbean.

The Lesser Antilles Island Arc is in many ways very similar to the more classic island arcs in the western Pacific (seismicity, volcanism, accretion of deformed sediments, etc.), but a very particular point of its morphology is the presence, at least in its southern part, of enormous masses of sediments originating from the South American continent. A comparison of section 1 in Fig. 2 with sections in other intraoceanic island arcs (New Hebrides, cf. MASCLE ET AL., 1977; Marianna, see KARIG, 1973) shows the great development and thick infilling of both the outer-arc and back-arc basins. In the same way, the very thick sedimentary cover of the Atlantic abyssal plain in front of the arc has been deformed during subduction of the crust and has created an enormous acretionary prism. Because the former trenches have been progressively buried under this prism, the deformation front has migrated away from this arc toward the abyssal plain, with a tectonic style of deformation made of broad anticlines thrust to the east. Another original sequence of such a growth of the acretionary prism is its rear overthrusting onto the Tobago Basin, in such a way that sediments are also accreted on the back part of the prism.

The structure of the two small oceanic areas behind the Lesser Antilles Island Arc, i.e. the Venezuela Basin and the Colombia Basin, have also been studied. They now appear as complex and heterogeneous basins whose basements could be of various ages and natures. Sediment distribution in these basins also varies greatly and appears to be directly linked to the type of the neighbouring margins. For instance, the development of active margins (like the north Venezuelan active margin) has induced a landward tilt of the basin, favouring turbiditic deposits in the depressions and trenches. An island arc such as the now extinct Aves Ridge, has supplied lava, ashes and/or volcano-clastic deposits. Deep-sea fans like the Magdalena fan may have blanketed a broad part of the abyssal plains with turbiditic deposits (see MUÑOZ, 1966). Thus the sedimentary history and probably also the crustal history of these basins cannot be explained as a whole, but rather by taking the history of

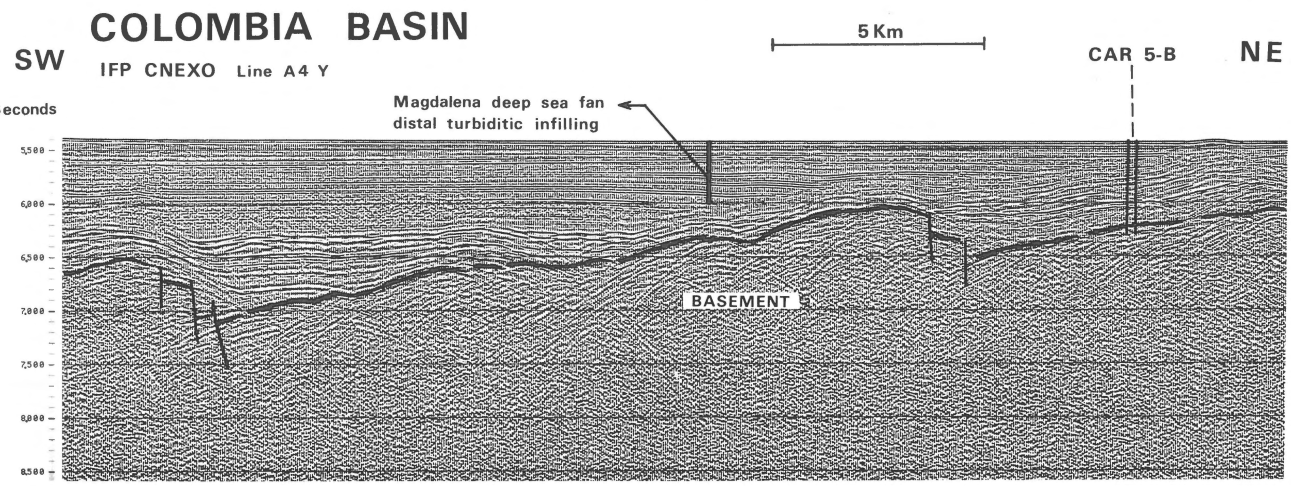

Fig. 13
IFP-CNEXO, Multichannel seismic line A4Y. Location on Fig. 1 and 12.

their margins into consideration.

But geophysical data cannot give an answer to all the questions. This is the reason why new deep-sea holes have been proposed by the Mediterranean-Caribbean subpanel of IPOD and the area in question has been surveyed by IFP-CNEXO. The following list briefly sums up some of their major objectives:

- to date the Atlantic oceanic crust in front of the Lesser Antilles Island Arc and to define the amount of subducted crust.
- Tectonic style of deformation in front of an acretionary prism, i.e. the Barbados Ridge.
- Nature and age of the basement of a back arc basin, i.e. the Grenada Basin. Age and nature of its sedimentary infilling, giving a complete Cenozoic biostratigraphic reference.
- Nature and age of different parts of the Venezuela and Colombia Basin crusts. Their age and lithology could be compared with the widespread volcanic events known on land.
- History of the north Venezuela active margin as it may be reflected in the Venezuela Basin abyssal plain at its foot.
- History of the communication of watermasses between Atlantic and Pacific Oceans.

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